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## Review of $Z'$ Physics at Future Colliders<sup>★</sup>

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### ABSTRACT

We present recent developments in the diagnostic study of heavy gauge bosons at future colliders with the emphasis on the determination of gauge couplings of  $Z'$  to quarks and leptons. Proposed diagnostic probes at future hadron colliders are discussed. The study of statistical uncertainties expected for the above probes at the LHC and  $M_{Z'} \simeq 1$  TeV shows that three out of four normalized couplings can be determined, thus allowing for a distinction between models. The complementary nature of the probes at future  $e^+e^-$  colliders is also discussed.

### 1. Introduction

Extended gauge structures, including heavy neutral ( $Z'$ ) and charged ( $W'$ ) gauge bosons, are an essential part of theories beyond the standard models, including grand unified theories (GUT) and superstring theory. If heavy gauge bosons turn out to have a mass in the few TeV region, future hadron colliders, the Superconducting Super Collider (SSC) and the Large Hadron Collider (LHC), would be an ideal place to discover them.<sup>†</sup>

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<sup>†</sup> For a review of present bounds on  $Z'$  see for example Ref. 1.

At such hadron colliders heavy neutral gauge bosons  $Z'$  with mass up to around 5 TeV can be produced and clearly detected via leptonic two fermion decays  $pp \rightarrow Z' \rightarrow \ell^+ \ell^-$  ( $\ell = e, \mu$ ).<sup>[2–5]</sup> After the discovery of a new gauge boson one would like to learn more about its properties. There would be a need to address and possibly separate different features: (i)  $Z'$  couplings to ordinary fermions, (ii) the nature of symmetry breaking, and (iii)  $Z'$  couplings to exotic fermions and supersymmetric partners.

A test of the symmetry breaking structures are the decays  $Z' \rightarrow W^+ W^-$ <sup>[6,7]</sup>, which are suppressed by  $Z - Z'$  mixing but still have a sizable rate due to the enhancement of the longitudinal components of the  $W$  bosons. However, they suffer from serious QCD backgrounds.<sup>[8,9]</sup> In theories with charged gauge bosons, *e.g.*, left-right (LR) symmetric models, the ratio  $M_{Z'}/M_{W'}$  plays an analogous role to the  $M_Z/M_W$  ratio (related to the  $\rho$  parameter) in the standard model. This ratio therefore yields indirect information on the nature of the Higgs sector.<sup>[10]</sup>

The study of  $Z'$  decays into exotic particles also yields useful information. In particular,  $W' \rightarrow \ell N$  and  $Z' \rightarrow NN$  and subsequent decays of heavy right-handed neutrinos  $N$  turn out to be useful probes for distinguishing the left-right models from those with only an additional  $U(1)$ .<sup>[11]</sup>

In the following we shall concentrate on the diagnostic study of  $Z'$  couplings to quarks and leptons. In Section 2 we address the corresponding probes at future hadron colliders. In Section 3 we present an analysis for extracting information about the couplings. In Section 4 a comparison with  $e^+e^-$  colliders is given. Conclusions are given in Section 5.

## 2. Probes for $Z'$ gauge couplings at hadron colliders

In the main production channels,  $pp \rightarrow Z' \rightarrow \ell^+ \ell^-$  ( $\ell = e, \mu$ ), one would be able to measure immediately the mass  $M_{Z'}$ , the width  $\Gamma_{tot}$  and the total cross section  $\sigma_{\ell\ell}$ . However,  $\sigma_{\ell\ell} = \sigma(pp \rightarrow Z')B$  is *not* a useful diagnostic probe for the  $Z'$  gauge couplings to quarks and leptons. While  $\sigma(pp \rightarrow Z')$ , the total production cross section, can be calculated to within a few percent for given  $Z'$  couplings, the branching ratio into leptons,  $B \equiv \Gamma(Z' \rightarrow \ell^+ \ell^-)/\Gamma_{tot}$ , is model dependent; it depends on the contribution of exotic fermions and supersymmetric partners to the  $Z'$  width, and thus it cannot be useful as a diagnostic test for the  $Z'$  gauge couplings. However, it would be a useful indirect probe for the existence of the exotic fermions or superpartners. On the other hand, from measurements of the total width<sup>[5]</sup>  $\Gamma_{tot}$ , and  $\sigma_{\ell\ell}$  one obtains  $\sigma\Gamma(Z' \rightarrow \ell^+ \ell^-) \equiv \sigma B \Gamma_{tot}$ , which probes the absolute magnitude of the gauge couplings.

In the following we will address signals which probe *relative strengths* of  $Z'$  gauge couplings. Until recently, the only recognized probe for the gauge couplings at future hadron colliders was the forward-backward asymmetry<sup>[2]</sup> in the main production channel  $pp \rightarrow Z' \rightarrow \ell^+ \ell^-$  ( $\ell = e$  or  $\mu$ ).<sup>‡</sup> There was a clear need to search for additional, complementary probes, thus triggering a renewed interest<sup>[7,13–21]</sup> in diagnostic probes of the  $Z'$  couplings. The previously poorly explored domain of  $Z'$  diagnostics is now a rich and ongoing field.

The nature of such probes can be classified according to the type of channel in which they can be measured:

(Ia) *The main production channels:*

- (A) Forward-backward asymmetry,<sup>[2]</sup>
- (B) Ratio of cross-sections in different rapidity bins,<sup>[20]</sup>
- (C) Corresponding asymmetries if proton polarization were available.<sup>[15]</sup>

(Ib) *Other two-fermion final state channels:*

- (D) Measurements of the  $\tau$  polarization in the  $pp \rightarrow Z' \rightarrow \tau^+ \tau^-$  channel,<sup>[14]</sup>
- (E) Measurements of the cross section in the  $pp \rightarrow Z' \rightarrow jet\ jet$  channel.<sup>[21,22]</sup>

(II) *The four-fermion final state channels:*

- (F) Rare decays  $Z' \rightarrow W \ell \nu_\ell$ ,<sup>[24,13]</sup>
- (G) Associated productions  $pp \rightarrow Z' V$  with  $V = (Z, W)$ <sup>[18]</sup> and  $V = \gamma$ <sup>[19]</sup>.

Probes under (Ia) constitute distributions, *i.e.*, “refinements”, in the main production channels. The forward-backward asymmetry (A) was long recognized as useful to probe a particular combination of quark and lepton couplings. On the other hand, the rapidity ratio (B)<sup>[20]</sup> was recognized as a useful complementary probe separating the  $Z'$  couplings to the  $u$  and  $d$  quarks due to the harder valence  $u$ -quark distribution in the proton relative to the  $d$ -quark. Probes (C) are very useful if proton polarization were available at future hadron colliders.

For probes in other than the main production channels (Ib) the background can be large. For (E) the QCD background may be difficult to overcome.<sup>[21,22]</sup> (D) provides another interesting possibility to address the  $Z'$  lepton couplings, while (E) is the only probe available for the left-handed quark coupling.<sup>[18]</sup>

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<sup>‡</sup> See also Ref. 12.

Probes in the four-fermion final state channels (II) have suppressed rates compared to the two fermion channels (Ia) and (Ib). In these cases one hopes to have enough statistics, and no attempt to study distributions seems to be possible.

Rare decays  $Z' \rightarrow f_1 \bar{f}_2 V$ , with ordinary gauge bosons  $V = (Z, W)$  emitted by Bremsstrahlung from one of the fermionic ( $f_{1,2}$ ) legs turn out to have sizable statistics,<sup>[24,13]</sup> which is due to a double logarithmic enhancement,<sup>[13]</sup> closely related to collinear and infrared singularities of gauge theories. They were studied in detail in Refs. 13, 16, 17. A background study<sup>[13,18]</sup> of such decays revealed that the only useful mode<sup>§</sup> without large standard model and QCD backgrounds is (F):  $Z' \rightarrow W \ell \nu_\ell$  and  $W \rightarrow \text{hadrons}$ , with the imposed cut  $m_{T\ell\nu_\ell} > 90$  GeV on the transverse mass of the  $\ell\nu_\ell$ . (This assumes that there is a sufficiently high efficiency for the reconstruction of  $W \rightarrow \text{hadrons}$  in events tagged by an energetic lepton. Further study of the QCD background and the jet reconstruction for such processes is needed.) The same mode with  $W \rightarrow \ell \nu_\ell$  may also be detectable<sup>[16]</sup> if appropriate cuts are applied.<sup>¶</sup> These modes probe a left-handed leptonic coupling.

Associated productions (F) turn out to be relatively clean signals<sup>[18]</sup> with slightly smaller statistics than rare decays. They probe a particular combination the gauge couplings to quarks and are thus complementary to rare decays.

At the SSC and the LHC the above signals are feasible diagnostic probes for  $M_{Z'} \lesssim 1\text{--}2$  TeV. For diagnostic study of  $Z'$  couplings large luminosity is important; for  $M_{Z'} \sim 1$  TeV, one expects about twice as many events at the LHC (projected luminosity  $10^{34}\text{cm}^{-2}\text{s}^{-1}$ ) than at the SSC (projected luminosity  $10^{33}\text{cm}^{-2}\text{s}^{-1}$ ). For higher  $Z'$  masses the number of events drops rapidly. For  $M_{Z'} \simeq 2$  TeV, the statistical errors on forward-backward asymmetry (A), the rapidity ratio (B), and rare decays (F) increase by a factor of 4, while those on associated productions (G) increase by a factor of 3. A reasonable discrimination between models and determination of the couplings may still be possible, primarily from the forward-backward asymmetry and the rapidity ratio. However, for  $M_{Z'} \simeq 3$  TeV the statistical errors on the first three quantities are larger by a factor of 13 than for 1 TeV, and there are not enough events expected for the associated production to allow a meaningful measurement. For  $M_{Z'} \gtrsim 3$  TeV, there is therefore little ability

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§  $Z' \rightarrow Z \ell^+ \ell^-$  does not significantly discriminate between models.

¶ A (remote) possibility of gaining useful information from  $Z' \rightarrow Z \nu_\ell \bar{\nu}_\ell$ <sup>[13,18,17]</sup> was recently resurrected.<sup>[23]</sup>

to discriminate between models.

### 3. Determination of gauge couplings at hadron colliders

We would now like to examine how well the various  $Z'$  couplings could be extracted from the above probes. We will mainly concentrate on probes (A), (B), (F) and (G), which, from our perspective, are most feasible. For definiteness, we consider the statistical uncertainties for  $M_{Z'} = 1$  TeV at the LHC. Eventually, the uncertainties associated with the detector acceptances and systematic errors will have to be taken into account.

We consider the following typical models:  $Z_\chi$  in  $SO_{10} \rightarrow SU_5 \times U_{1\chi}$ ,  $Z_\psi$  in  $E_6 \rightarrow SO_{10} \times U_{1\psi}$ ,  $Z_\eta = \sqrt{3/8}Z_\chi - \sqrt{5/8}Z_\psi$  in superstring inspired models in which  $E_6$  breaks directly to a rank 5 group, and  $Z_{LR}$  in LR symmetric models. For conventions in the neutral current interactions see Ref. 25. In the following we assume family universality, neglect  $Z - Z'$  mixing and assume  $[Q', T_i] = 0$ , which holds for  $SU_2 \times U_1 \times U'_1$  and LR models. Here,  $Q'$  is the  $Z'$  charge and  $T_i$  are the  $SU_{2L}$  generators.

The relevant quantities<sup>[18, 20]</sup> to distinguish different theories are the charges,  $\hat{g}_{L2}^u = \hat{g}_{L2}^d \equiv \hat{g}_{L2}^q$ ,  $\hat{g}_{R2}^u$ ,  $\hat{g}_{R2}^d$ ,  $\hat{g}_{L2}^\nu = \hat{g}_{L2}^e \equiv \hat{g}_{L2}^\ell$ , and  $\hat{g}_{R2}^\ell$ , and the gauge coupling strength  $g_2$ . The signs of the charges will be hard to determine at hadron colliders. Thus the following four “normalized” observables can be probed:<sup>[18]</sup>

$$\gamma_L^\ell \equiv \frac{(\hat{g}_{L2}^\ell)^2}{(\hat{g}_{L2}^\ell)^2 + (\hat{g}_{R2}^\ell)^2}, \quad \gamma_L^q \equiv \frac{(\hat{g}_{L2}^q)^2}{(\hat{g}_{L2}^\ell)^2 + (\hat{g}_{R2}^\ell)^2}, \quad \tilde{U} \equiv \frac{(\hat{g}_{R2}^u)^2}{(\hat{g}_{L2}^q)^2}, \quad \tilde{D} \equiv \frac{(\hat{g}_{R2}^d)^2}{(\hat{g}_{L2}^q)^2}. \quad (1)$$

The values of  $\gamma_L^\ell$ ,  $\gamma_L^q$ ,  $\tilde{U}$ , and  $\tilde{D}$  for the above models are listed in Table I.

The forward-backward asymmetry (A) is defined as:  $A_{FB} = \frac{\left[ \int_0^{y_{max}} - \int_{-y_{max}}^0 \right] [F(y) - B(y)] dy}{\int_{-y_{max}}^{y_{max}} [F(y) + B(y)] dy}$ ,

while the rapidity ratio (B) is defined as:<sup>[20]</sup>  $r_{y1} = \frac{\int_{-y1}^{y1} [F(y) + B(y)] dy}{(\int_{-y_{max}}^{-y1} + \int_{y1}^{y_{max}}) [F(y) + B(y)] dy}$ . Here

$F(y) \pm B(y) = [\int_0^1 \pm \int_{-1}^0] d \cos \theta (d^2 \sigma / dy d \cos \theta)$ , where  $y$  is the  $Z'$  rapidity and  $\theta$  is the  $\ell^-$  angle in the  $Z'$  rest frame. The rapidity range is from  $\{-y_{max}, y_{max}\}$ .  $y_1$  is chosen in a range  $0 < y_1 < y_{max}$  so that the number of events in the two bins are comparable. At the LHC ( $y_{max} \simeq 2.8$ ) for  $M_{Z'} \simeq 1$  TeV, and  $y_1 = 1$  turns out to be an appropriate choice. For rare decays (F) one defines:<sup>[13]</sup>  $r_{\ell \nu W} \equiv \frac{B(Z' \rightarrow W \ell \nu_\ell)}{B(Z' \rightarrow \ell^+ \ell^-)}$ , in which one sums over  $\ell = e, \mu$  and over  $W^+, W^-$ . For the associated productions (G) one defines<sup>[18]</sup> the ratios:  $R_{Z'V} = \frac{\sigma(pp \rightarrow Z'V) B(Z' \rightarrow \ell^+ \ell^-)}{\sigma(pp \rightarrow Z') B(Z' \rightarrow \ell^+ \ell^-)}$  with  $V = (Z, W)$

	$\chi$	$\psi$	$\eta$	$LR$
$\gamma_L^\ell$	$0.9 \pm 0.018$	$0.5 \pm 0.03$	$0.2 \pm 0.015$	$0.36 \pm 0.007$
$\gamma_L^q$	0.1	0.5	0.8	0.04
$\tilde{U}$	$1 \pm 0.18$	$1 \pm 0.27$	$1 \pm 0.14$	$37 \pm 8.3$
$\tilde{D}$	$9 \pm 0.61$	$1 \pm 0.41$	$0.25 \pm 0.29$	$65 \pm 14$
$\rho_{ud}$	-0.19	-0.24	-0.66	0.93

**Table I**<sup>[20]</sup> Values of  $\gamma_L^\ell$ ,  $\gamma_L^q$ ,  $\tilde{U}$ , and  $\tilde{D}$  for the  $\chi$ ,  $\psi$ ,  $\eta$ , and  $LR$  models. The error bars indicate how well the coupling could be measured at the LHC for  $M_{Z'} = 1$  TeV.  $\rho_{ud}$  indicates the correlation coefficient between  $\tilde{U}$  and  $\tilde{D}$ . Except for the  $\chi$  model the correlation between  $\gamma_L^\ell$  and ( $\tilde{U}$ ,  $\tilde{D}$ ) are negligible.

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**Figure 1** 90% confidence level ( $\Delta\chi^2 = 6.3$ ) contours for the  $\chi$ ,  $\psi$  and  $\eta$  models are plotted for  $\tilde{U}$ , versus  $\tilde{D}$ , versus  $\gamma_L^\ell$ . The input data are for  $M_{Z'} = 1$  TeV at the LHC and include statistical errors only. The axes  $\tilde{U}$ ,  $\tilde{D}$ , and  $\gamma_L^\ell$  are rescaled by a factor 20, 2, and 40, respectively.

decaying into leptons and quarks, and  $V = \gamma$  with an imposed  $p_{T\gamma} \geq 50$  GeV cut.  $\ell$  includes both  $e$  and  $\mu$ .

Statistical errors of the above probes for  $M_{Z'} = 1$  TeV at the LHC are given in Ref. 20. They turn out to be sufficiently small to distinguish between models. The six quantities  $A_{FB}$ ,  $r_{y_l}$ ,  $r_{\ell\nu W}$ , and  $R_{Z'V}$  with ( $V = Z, W, \gamma$ ) yield significant information on three ( $\gamma_L^\ell$ ,  $\tilde{U}$  and  $\tilde{D}$ ) out of four normalized gauge couplings of ordinary fermions to the  $Z'$ . The fourth normalized coupling  $\gamma_L^q$  could be determined<sup>[18]</sup> by a measurement of the branching ratio  $B(Z' \rightarrow q\bar{q})$  (E). Recent studies indicate that this might be possible.<sup>[21,22]</sup>

To study with what precision these couplings could be determined, a combined  $\chi^2$  analysis of these observables has been performed.<sup>[20]</sup> Only the statistical uncertainties have been included and correlations between the observables have been ignored. The results are given in Table I. In particular,  $\gamma_L^\ell$  can be determined very well (between 2% and 8% for the  $\chi$ ,  $\psi$ , and  $\eta$  models), primarily due to the small statistical error for the rare decay mode  $Z' \rightarrow W\ell\nu_\ell$ . On the other hand the quark couplings have larger uncertainties, typically 20% for  $\tilde{U}$ , and an absolute error of  $\sim 0.3 - 0.6$  for  $\tilde{D}$  (except  $Z_{LR}$ ). In Figure 1 90% confidence level ( $\Delta\chi^2 = 6.3$ ) contours<sup>\*</sup> are given in a three-dimensional plot for  $\tilde{U}$  versus  $\tilde{D}$  versus  $\gamma_L^\ell$  for the  $\eta$ ,  $\psi$  and  $\chi$  models. The  $LR$  model has  $\tilde{U}$  and  $\tilde{D}$  in a different region of the parameter space (see Table I). From Figure 1 it is clear that one can distinguish well between different models.

We would also like to comment briefly on the determination of heavy charged ( $W'$ ) gauge boson couplings. While the forward-backward asymmetry in the main production channels  $pp \rightarrow W' \rightarrow \ell\nu_\ell$  ( $\ell = e, \mu$ ) probes some combination of gauge couplings, it does not distinguish  $\hat{g}_{L2}$  from  $\hat{g}_{R2}$  couplings. On the other hand rare decays  $W'^{\pm} \rightarrow W\ell^+\ell^-$  and associated productions  $pp \rightarrow W'^{\pm}W^{\mp}$  are strongly suppressed<sup>[13,7,18]</sup> if  $W'$  has only  $\hat{g}_{R2}$  couplings, as in the LR symmetric models. In models where  $W'$  has  $\hat{g}_{L2}$  couplings, *e.g.*, the so-called un-unified models,<sup>[26]</sup> the corresponding rates are, however, not suppressed; primarily due to the larger gauge couplings of  $W'$ , the corresponding rates allow for determination of  $\hat{g}_{L2}$  couplings for  $M_{W'}$  up to around 3 TeV.<sup>[27]</sup>

#### 4. Comparison with $e^+e^-$ colliders

Future  $e^+e^-$  colliders (next linear collider (NLC)) with large enough center of mass energy, *e.g.*,  $\sqrt{s} = 2$  TeV, could provide a clean way to discover and study

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\* The 90% confidence level contours for projections on the more familiar two-dimensional parameter subspaces correspond to  $\Delta\chi^2 = 4.6$ .

the properties of a  $Z'$ . A more likely possibility is a NLC with center of mass energy in the range of  $\sqrt{s} = 500$  GeV, which would, due to interference effects of the  $Z'$  propagator with the  $\gamma$  and  $Z$ , provide complementary diagnostics of the  $Z'$ .<sup>[28,29]</sup> In order to distinguish between models the standard probes  $\sigma_{lep}$ ,  $A_{FB}^{lep}$  and  $R^{had} = \frac{\sigma^{had}}{\sigma^{lep}}$ , as well as  $A_{LR}^{lep, had}$  (if the  $e$  polarization is available) can be used.<sup>[28,29]</sup> Such probes allow for distinguishing between models for  $M_{Z'}$  for up to around 1 TeV. In such studies one has to take into account radiative QED corrections and the experimental set up.<sup>[28]</sup>

When addressing diagnostics of  $Z'$  gauge couplings<sup>[30]</sup> the above probes are complementary to the ones at future hadron colliders (as discussed in Chapters 2 and 3). In particular, since at the NLC the effects of a  $Z'$  are due to the  $Z'$  propagator interference terms, the  $Z'$  total width  $\Gamma_{tot}$  is not measurable, while the mass  $M_{Z'}$  and the absolute value of the gauge coupling  $g_2$  is measurable only in a combination, *e.g.*,  $\frac{g_2^2(\hat{g}_{V2}^\ell)^2}{M_{Z'}^2}$ . On the other hand, the four normalized charges, *e.g.*,  $\frac{\hat{g}_{A2}^\ell}{\hat{g}_{V2}^\ell}$ ,  $\frac{\hat{g}_{R2}^u}{\hat{g}_{V2}^\ell}$ ,  $\frac{\hat{g}_{R2}^d}{\hat{g}_{V2}^\ell}$ , and  $\frac{\hat{g}_{L2}^q}{\hat{g}_{V2}^\ell}$ <sup>†</sup> (and not only the corresponding normalized *squares* of charges as in Eq.(1)) can be probed.  $\sigma_{lep}$  and  $A_{FB}^{lep}$  probe  $\frac{(\hat{g}_{A2}^\ell)^2}{(\hat{g}_{V2}^\ell)^2}$ , which is complementary to  $\gamma_L^\ell$ . On the other hand,  $R^{had}$  provides information on one combination of normalized quark couplings. If the  $e$  polarization were available the  $A_{LR}^{lep}$  would be a sensitive probe for  $\frac{\hat{g}_{A2}^\ell}{\hat{g}_{V2}^\ell}$ , while  $A_{LR}^{had}$  would yield information on another combination of normalized quark couplings. The possibility of flavor tagging in the heavy quark ( $c, b, t$ ) sector would allow for measuring  $R^{u,d}$  and  $A_{FB}^{u,d}$ , which would in turn provide complementary information on all the quark couplings.

## 5. Conclusions

If there are new heavy gauge bosons with  $M_{Z'} \lesssim 1 - 2$  TeV future hadron colliders would not only be an ideal place for their discovery, but would also provide a fertile ground to learn more about their properties, in particular, their couplings to quarks and leptons. Future  $e^+e^-$  colliders with  $\sqrt{s} \sim 500$  GeV would in turn allow for complementary studies of heavy gauge boson properties.

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<sup>†</sup> Since the  $\ell$  couplings to  $Z$  have the property  $\hat{g}_{L1}^\ell \simeq -\hat{g}_{R1}^\ell$  it turns out that the above probes single out the  $Z'$  leptonic couplings primarily in the combinations  $\hat{g}_{V2,A2}^\ell \equiv \hat{g}_{L2}^\ell \pm \hat{g}_{R2}^\ell$ .



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